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Research & Development

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EDITORIAL

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CIRCLE 101 ON INQUIRY CARD

$119 billion for R&D in the United States in 1986

An increase of almost $10 billion in total funding will keep research and development ahead of the general economy in growth, even though the growth rate is slower than before.

C. J. Mosbacher
Consultant, *R&D* magazine

THIS YEAR brings an end to a succession of double-digit increases in R&D funding. At least that is what our forecast results indicate, with an overall increase of slightly less than 9% from 1985 funding. To be exact, the increase is 8.97% from $109.2 billion to $119.0 billion.

But with inflation forecast at 4.5%, an estimate based on the consensus of economists' predictions at the end of November, that's enough for us to predict with some confidence that the R&D field once again will exhibit real growth this year. And, with real growth in the gross national product forecast, on the same basis, as 3.5% for 1986, the proportion of gross national product spent on R&D will increase from the estimated 2.8% share in 1985.

Included in the total are $58.0 billion from the industrial sector, $57.2 billion in Federal government funding, and $3.8 billion from other sources that include the academic community and other nonprofit organizations. In the performance of R&D, industry will spend $88.1 billion, the Federal government $14.1 billion, and the academic and nonprofit sector $16.8 billion.

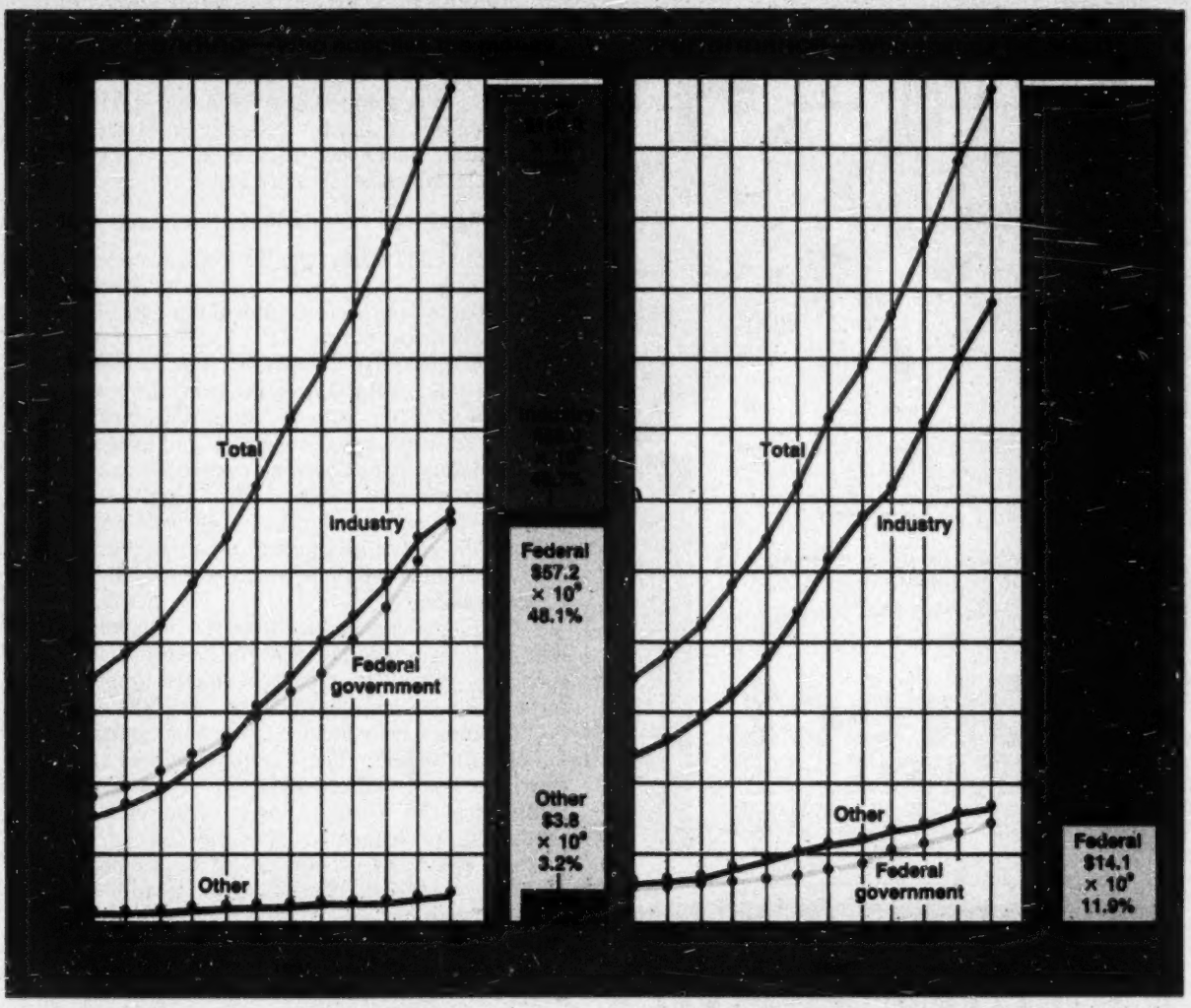
This means that industry will provide 48.7% of the total funding and will spend 74.0%. The Federal government will provide 48.1% and will spend in its own facilities 11.9%. The academic and nonprofit groups will provide 3.2% but will spend 14.1% during calendar 1986.

As in previous years, our first step in preparing this forecast was to revise our 1985 forecast in the light of later government data and developments during the year. We tracked changes in Federal funding as appropriated funds were obligated to specific projects. For the industrial sector, we scanned financial reports and other documents, monitored changes in plans as reported in the media, and spoke personally with executives of a number of companies. We did the same with leaders of academic and other nonprofit organizations.

The information thus garnered also was invaluable in formulating our 1986 forecast.

For funding for 1985, the R&D forecast was $55.0 billion from industry, $51.5 billion from the Federal government, and $3.5 billion from other sources. The forecast for performance was $81.2 billion by industry, $12.4 billion by the Federal government in its own facilities, and $16.4 billion by other sectors, for a total of $110.0 billion.

The National Science Foundation, in its "Science Resources Studies Highlights," NSF 85-304, dated January 31, 1985, projected funding as $54.0 billion from industry, $51.5 billion from the Federal government, and $3.7 billion from other sources. Corresponding figures for performance were $80.0 billion, $13.4 billion,



and $15.8 billion, for a total of $109.2 billion projected for 1985 R&D.

For funding, NSF's projection agreed with our forecast for the Federal government. However, our later data indicate that industry funding should be $54.2 billion and funding by the academic and other nonprofit sectors should be $3.5 billion.

For performance, we agree with NSF's $80.0 billion for industry, in line with the significant adjustment for industry funding during the year. However, later data indicate that NSF overestimated, albeit slightly, performance in Federal laboratories and underestimated the growth of academic and nonprofit research. Our revised performance figures are $13.2 billion for the Federal government and $16.0 billion in the academic and nonprofit sector.

Thus in 1985, industry provided 49.6% of R&D funds, the Federal government 47.2%, and other sources 3.2%. Corresponding numbers for performance are 73.3%, 12.1%, and 14.7%.

These revised 1985 data were used to calculate the increases or decreases in the remainder of this forecast.

Industry funding increases more slowly

From 1984 to 1985, industry increased its R&D funding by 11.5%. Early in 1985, all indications were that this rate of increase would continue. Then slumps in the computer, semiconductor, and other areas occurred. A few firms, mostly those already known for countercyclical adjustments to R&D funding, increased support, but the majority of firms adjusted their plans in line with reduced revenues. Projections of lower growth in gross national product became common.

Late in 1985, the McGraw-Hill Economics unit of McGraw Hill Inc. reported that their annual survey of capital spending indicated a 1% cut in industry plans for 1986. For durable-goods makers, however, this study projected an increase of 6.8% for aerospace capital spending and an increase of 7.8% for instruments.

Copeland Economics Group Inc. confirmed lower spending plans by industry in its report to the Laboratory Apparatus Section of the Scientific Apparatus Makers Assn. during November. Copeland projected a 1.0% increase from 1985 to 1986, following a 5.6% increase from 1984 to 1985. Comparable Copeland data are a 14.7% increase in the governmental sector and a 1.7% decrease in the educational sector.

It's important to note at this point that R&D funding does not track capital spending. If a relationship exists at all, R&D leads capital spending, but that is an intuitive statement. Studies to quantify the time element have failed, leading only to generalities.

But general business conditions do affect both

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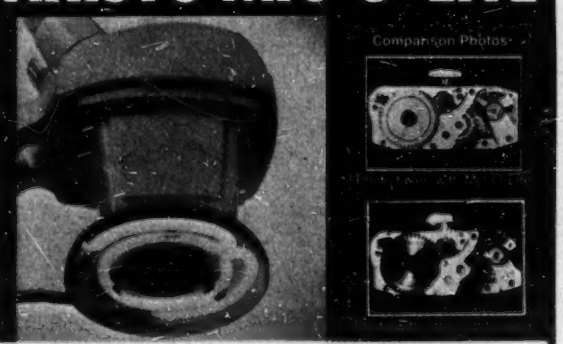

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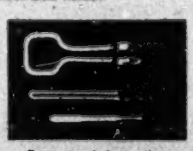

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CIRCLE **155** ON INQUIRY CARD

capital and R&D funding. Last-minute checks with industry leaders indicated that 1986 funds would increase slightly over 7% from 1985 levels.

Our forecast for industry funding is $58 billion. With transfers of funds, primarily from the Federal government, we expect industry to perform 74% of 1986 R&D, which is $88.1 billion.

Double-digit increase again for Federal funds

At the end of July, the National Science Foundation reported in NSF 85-322 that Federal R&D funds were budgeted to increase 15% in the fiscal 1986 budget. Nearly three fourths of the $58.3 billion total supported defense-related activities. That was a 23% increase in defense R&D from the previous year.

Budgets differ from appropriations by Congress, which differ from actual obligation and expenditure of Federal funds. It has become customary for the Congress to act on many appropriations after the beginning of the fiscal year, which makes forecasting more difficult. By the end of November, adequate decisions had been made to allow some precision in predicting 1986 Federal funds.

One significant change from the budget is a $1 billion cut in Strategic Defense Initiative ("Star Wars") spending. In general, Congress shaved funds from almost all R&D items in the budget for FY86.

Calendar 1986 includes the first quarter of the Federal fiscal 1987. The Gramm-Rudman legislation restricts possible deficits and could impact R&D funds in the fiscal 1987 budget. For example, indications already point to curtailment of energy R&D.

All this leads us not to expect a repeat of the 14.2% increase from 1984 to 1985. Our studies indicate an increase of just over 11% in Federal funding.

Our forecast for Federal calendar 1986 funding is $57.2 billion. We expect $14.1 billion to be spent on R&D in the government's own facilities. That's an increase of 6.8% from 1985.

Universities and nonprofits gain

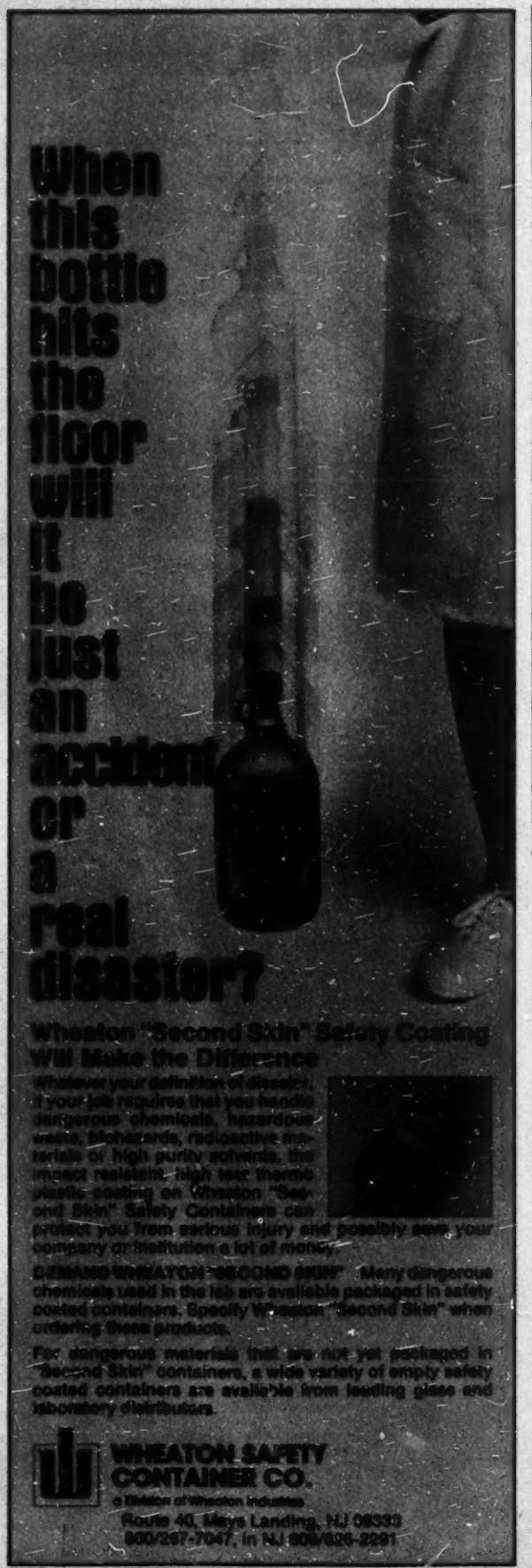
The academic and nonprofit sector had the smallest gain of the three sectors from 1984 to 1985 in funding, 9.4%. The increase from 1985 to 1986 is just slightly less according to our studies, 8.6%. Our forecast is that this sector will provide $3.8 billion.

Reluctance to accept Dept. of Defense funding of academic R&D is declining. Nonprofit R&D centers are becoming vital to industry in such areas as semiconductor processing and computer development.

Counterbalancing these developments is the decreasing rate of increase in funds available from the Federal government and industry. Our forecast, therefore, is that performance of R&D in this sector will rise 3.8% to $16.8 billion.

Performance of R&D in the academic and nonprofit sector thus becomes a slightly smaller part of the total, falling from 14.7% in 1985 to 14.1%. In the Federal sector, performance goes from 12.1% to 11.9% of the total. Conversely, the industrial sector rises slightly, from 73.3% to 74% of the total.

These changes are insignificant compared to the limits of accuracy of this forecast. All these data show is that there has been essentially no change in the patterns of distribution of R&D funds. R&D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OPINION POLL RESULTS

Strong reader interest in China as market, workplace

READERS of *Research & Development* respond favorably to the efforts of mainland China to establish technology and trade contacts with Western nations.

In response to a recent Opinion Poll Questionnaire, more than 50% say that they are working on a product which could be marketed in China now. Fully 85% believe that it would be wise for Western firms to try to develop markets in China. And more than half of the respondents said that they would accept a transfer to work a year or more in China.

The same questions were asked of our readers in a 1979 survey and, with two exceptions, the answers were within three percentage points of being the same in both surveys. In one change, 36% of respondents now favor substantial capital commitments in China, compared to 28% in 1979. In the other, 36% report having had representatives of the PRC as visitors or trainees at their firms recently. The figure was 18% in 1979.

Complete results of the recent survey follow:

1. *Does your principal work involve a product which could be marketed in China?*
   a. Now ..... 52% c. Never (or no) 17%
   b. Only later ..... 16 d. Don't know 14

2. *If your answer to Question 1 was a or b, would the market for your product be domestic (as opposed to sales to industry)?*
   a. Yes ..... 32% b. No 68%

3. *Do you think it would be wise for Western firms to try to develop markets in China?*
   a. Yes ... 85% b. No .... 7% c. No opinion 8%

4. *Do you think it would be wise for Western firms to establish substantial capital commitments in China?*
   a. Yes ... 36% b. No ... 42% c. No opinion ... 22%

5. *Have you had representatives of the People's Republic of China as visitors or trainees at your firm recently?*
   a. Yes ... 36% b. No ... 51% c. Don't know ... 13%

6. *Have you ever visited or worked in China?*
   a. No ..... 91% c. A few weeks 2%
   b. A few days ..... 4 d. Longer 1

7. *Do you speak any Chinese dialect?*
   a. Yes ..... 4% b. No 96%

8. *Would you accept a transfer to work a year or more in China?*
   a. Yes ..... 51% b. No 49%

CIRCLE 209 ON INQUIRY CARD

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Research & Development

FEBRUARY 1986

TECHNICAL PUBLISHING

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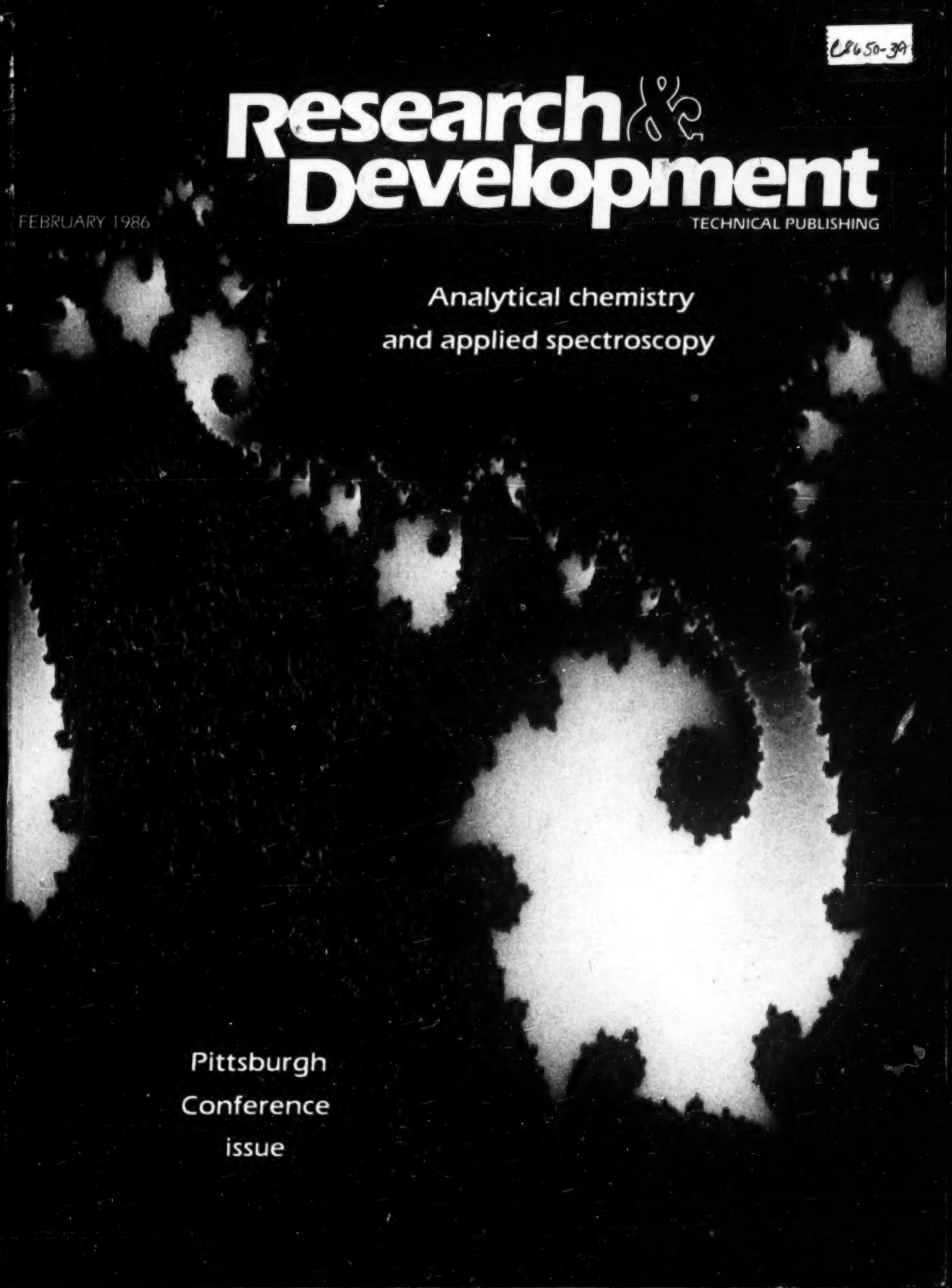
and applied spectroscopy



Pittsburgh
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Research & Development

SERVING THE $214-BILLION WORLDWIDE R&D INDUSTRY

Fractal behavior in dielectric spectroscopy. **See p 72.**

EDITORIAL

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ABOUT THE COVER

These computer-generated images result from an application of fractal geometry, a mathematical treatment of real shapes that does not depend on approximation by the triangles, circles, and squares of conventional geometry. Fractal geometry includes the notion of self-similarity—the tendency of natural forces to repeat themselves.

This concept is used by researchers in many fields. An article about one of them begins on page 72. It concerns dielectric spectroscopy and the development and degradation of colloidal structures.

The cover photo, supplied by IBM's Research Div. (© 1984), was made by H.O. Peitgen and R. Richter of Univ. of Bremen.

NEWS

Science policy: Work force changes are on the way for R&D; OTA confirms that gender limits research careers

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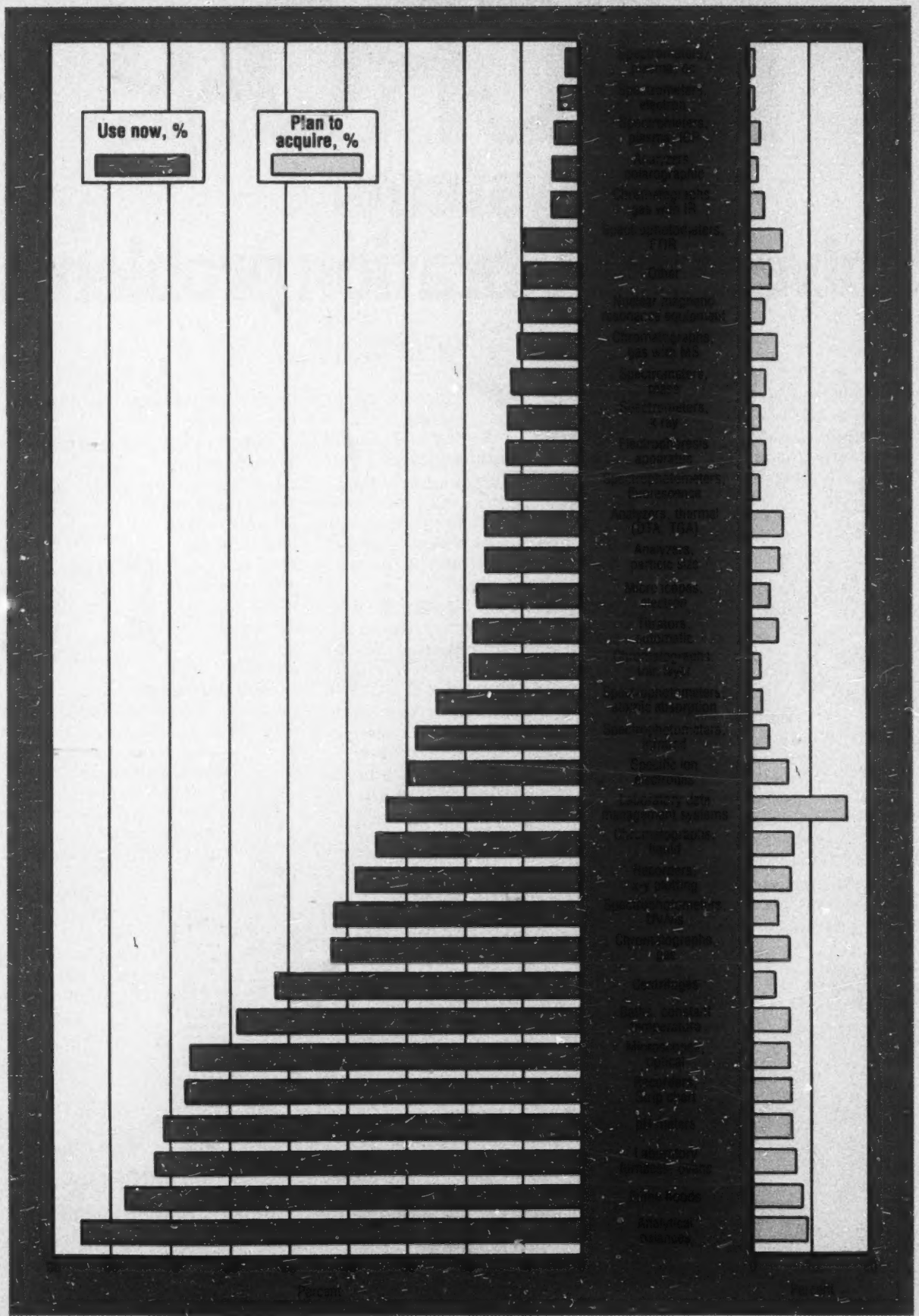

Use now, %
Plan to acquire, %
Percent
Percent

C.J. Mosbacher
Consultant, *R&D* magazine

TRENDSURVEY

Use of analytical instruments and equipment, 1986

Changes in demographics cloud the results of our annual survey of the present and planned use of 33 types of instruments, but average plans to acquire decrease only slightly.

AT FIRST GLANCE, the results of our latest annual Trendsurvey are troublesome. Average present use of analytical instruments and equipment drops to 30.7% from 1985's 31.3%. Average plans to acquire fall to 4.67% from last year's 5.13%. That is almost a 2% drop in present use and almost a 9% drop in plans to acquire.

But that is on the basis of the raw data, and overlooks a significant change in the demographics of the respondents, particularly in the disciplines represented.

Engineering climbs almost 24% to 25.6% of the total sample, while those in life science or medicine jump almost 7% to 20.9% of the total. At the same time, those in physical science drop some 13% to 20.9% of the total, and respondents giving no answer to the discipline question climb more than 50% to 4.1% of the total sample.

Some idea of the importance of this is revealed by an examination of the data that are tabulated with this article. The highest present use is recorded for only three categories of instruments and equipment by the engineering discipline: electron microscopes, strip-chart recorders, and x-y plotting recorders. For plans to acquire, the engineering discipline keeps top honors only for the two recorder categories.

Life science or medicine shows highest present use for only 10 categories, which drops to 8 categories for plans to acquire: centrifuges, thin-layer chromatographs, electrophoresis apparatus, pH meters, specific ion electrodes, fluorescene spectrophotometers, UV/vis spectrophotometers, and automatic titrators.

Conversely, physical science—whose representation fell—has the highest percentages for 20 categories in present use and 23 categories in plans to acquire.

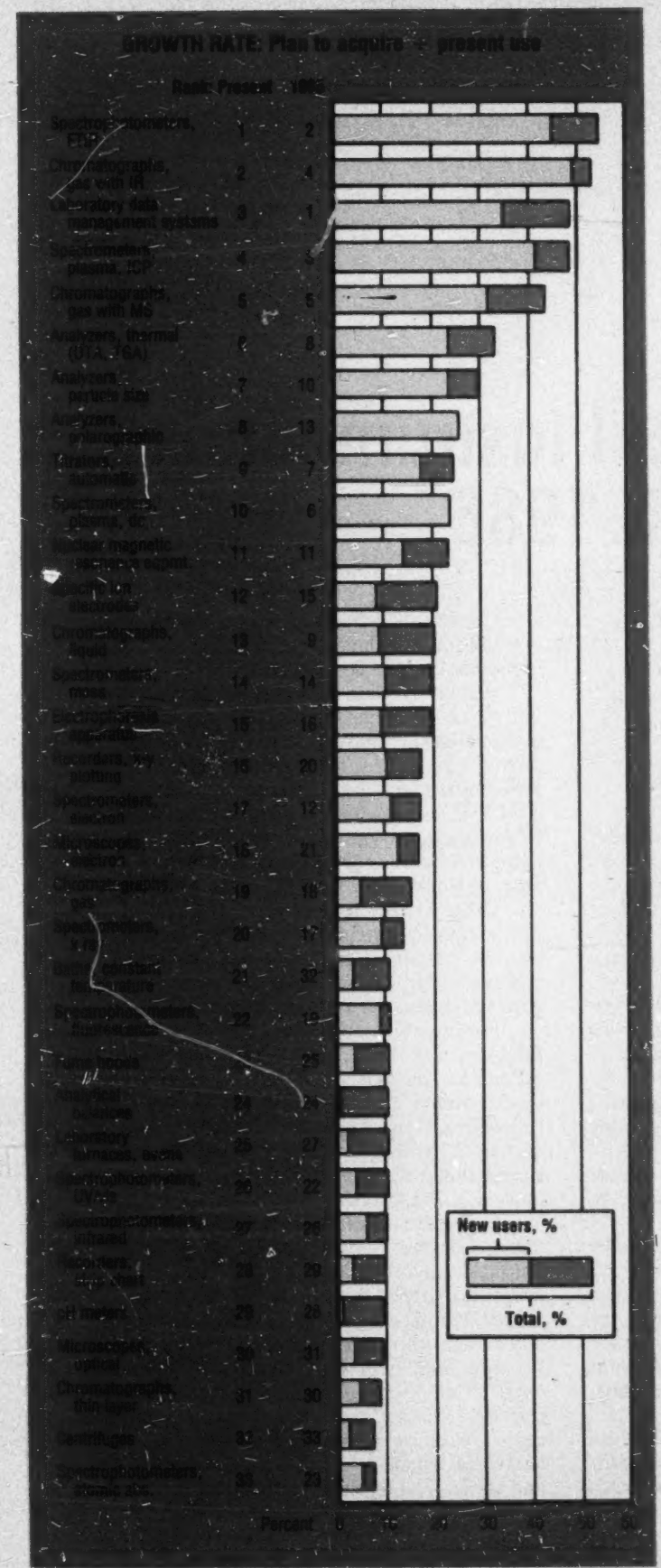
With these data in mind, one is not surprised to find that normalizing the results on the basis of changes in disciplines, employers, and job functions leads to a different picture. After normalizing so that 1986 data are comparable to 1985's, average present use this year is 31.4%, essentially the same as last year's 31.3%. Normalizing also raises this year's average plans to acquire to 4.78%, only 0.35% below the average for last year, or less than a 7% drop.

Other ways to look at the data include examining the number of categories that show increases or decreases, examining the magnitude of those changes, and examining the ranking or order of the various categories of instruments and equipment.

For present use, 14 categories show increases, 1 is the same, and 18 show losses from last year. The largest gainers are laboratory data management systems, up 3.0 points from 30.1% to 33.1%, and laboratory furnaces and ovens and electrophoresis apparatus, each up 2.7 points. Losers are topped by infrared spectrophotometers, down 5.3 points; analytical balances down 4.5; and gas chromatographs, down 3.8.

In plans to acquire, 10 categories are up and 23 are down. Constant-temperature baths gained 1.3 points, thermal analyzers 1.2, and x-y plotting recorders 0.9. Losers are topped by liquid chromatographs, down 2.9 points; laboratory data management systems, down 2.4; and gas chromatographs, down 2.0 points.

Rankings by present use are shown in the first bar chart for all 33 categories and "other" on a total sample basis. On that same basis, rankings for plans to acquire are led by laboratory data management systems, analytical balances, fume hoods, laboratory furnaces and ovens, and liquid chromatographs. Last year, liquid chromatographs occupied third place, fume hoods fourth, and gas chromatographs fifth, while furnaces and ovens were in seventh place.



Rankings by growth rate (plans to acquire divided by present use for each category) are shown in the second bar chart, which also shows last year's rankings on this basis. The growing importance of infrared techniques is evident in the changes in the uppermost rankings.

Another indicator of changes from year to year is the portion of respondents not giving any answers for present use or plans to acquire. In the present Trendsurvey, 2.7% did not indicate present use of any instument, compared to 2.1% last year. For plans to acquire, "no" answers rose to 44% this year from 39.4% in last year's study.

As in earlier studies, the geographic distribution of respondents parallels the circulation of *R&D* magazine. This validates the results because that circulation is kept in proportion to the distribution of funds and personnel in the field. New England accounts for 6.7% of the respondents to the Trendsurvey, the Middle Atlantic region 18.3, East North Central 23.1, West North Central 8.1, South Atlantic 14.6, East South Central 3.9, West South Central 8.2, Mountain 4.8, and Pacific 12.3%.

By discipline, which was referred to earlier, 25.6% list engineering, 49.4 physical science, 20.9 life science or medicine, while 4.1 gave no answer. For last year's Trendsurvey, the comparable data were 20.7% engineering, 56.9 physical science, 19.6 life science or medicine, and 2.9 no answer.

By employer, 58.2% work in industry, 16.6 in universities, 14.2 in government, 2.9 in nonprofit organizations, 2.7 in medical research centers, 3.1 other, and 2.3 no answer. Corresponding data for last year were 59.2% industry, 14.1 universities, 16.0 government, 3.1 nonprofit, 2.4 medical research, 4.0 other, and 1.2 no answer.

By job function, 3.3% are corporate officers, 8.4 R&D executives, 15.2 project managers, 65.3 professional staff, 5.5 other, ans 2.3 no answer. This is virtually the same as last year, when the corresponding figures were 4.0 corporate officers, 8.2 R&D executives, 13.6 project managers, 67.2 professional staff, 5.0 other, and 1.8 no answer.

This Trendsurvey was conducted by including a prepaid business reply card in a mailing to *R&D* readers in the United States in late September 1985. To meet deadlines, only replies received by early November could be included in the data here. R&D

GROWTH RATE (bar chart at left) is calculated with present use as base for each instrument category. Total includes all those who plan to acquire; new users are those who do not presently use that instrument but who plan to acquire. Difference is present users planning to acquire additional or replacement units in that particular instrument category.

PRESENT AND PLANNED USE: Data from 1,539 respondents * = 1986	Use now								Plan to acquire within 1 yr								Browse rate = plan to acquire + by present use				
	Total n=1,539		Engineering labs		Physical sci labs		Life science & medical labs		Total		Engineering labs		Physical sci labs		Life science & medical labs		Total		Engineering labs		Physical sci labs	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	%	No.	%	No.	%	No.
Analytical balances	1,311	85.2 *89.5	284	72.1	688	90.4	292	71.0	141	9.2 *10.7	31	7.9	61	10.6	25	7.8	10.8	121	9.2	20	1.5
Analyzers, particle size	253	16.4 *16.3	80	20.3	137	18.0	27	6.4	75	4.9 * 4.7	21	5.3	44	5.8	9	2.8	29.6	16	6.3	59	23.3
Analyzers, polarographic	67	4.4 * 7.1	7	1.8	48	6.3	9	2.8	17	1.1 * 1.6	7	1.8	9	1.2	1	0.3	25.4	—	—	17	25.4
Analyzers, thermal (DTA, TGA)	252	16.4 *14.0	74	18.8	157	20.6	12	3.7	83	5.4 * 4.2	13	3.3	63	8.3	7	2.2	32.9	24	9.5	59	23.4
Baths, constant temperature	904	58.7 *59.2	172	43.7	454	59.7	244	76.0	101	6.6 * 5.3	21	5.3	56	7.4	23	7.2	11.2	65	7.2	36	4.0
Centrifuges	807	52.0 *54.9	101	25.6	404	53.1	283	82.6	61	4.0 * 4.2	8	2.0	27	3.6	23	7.2	7.6	42	5.2	19	2.4
Chromatographs, gas	656	42.6 *46.4	109	27.7	401	52.7	121	37.7	102	6.6 * 8.6	16	4.0	63	8.3	16	5.0	15.6	65	9.9	37	5.6
Chromatographs, gas with IR	73	4.7 * 4.4	22	5.6	41	5.4	8	2.5	39	2.5 * 2.2	9	2.3	24	3.2	5	1.6	53.4	21	4.1	35	48.0
Chromatographs, gas with MS	164	10.7 *11.7	28	6.6	112	14.7	22	6.9	71	4.6 * 4.8	7	1.8	45	5.9	16	5.0	43.3	19	11.6	52	31.7
Chromatographs, liquid	539	35.0 *34.0	58	14.7	299	39.3	163	50.8	109	7.1 *10.0	9	2.3	77	10.1	21	6.5	20.2	57	10.6	52	9.6
Chromatographs, thin layer	300	19.5 *19.3	20	5.1	154	20.2	115	35.8	26	1.7 * 1.9	4	1.0	12	1.6	6	1.9	8.7	12	4.0	14	4.7
Electrophoresis apparatus	192	12.5 * 9.8	12	3.0	56	7.4	118	36.8	38	2.5 * 2.0	2	0.5	15	2.0	21	6.5	19.8	19	9.9	19	9.9
Fume hoods	1,196	77.7 *79.3	264	67.0	633	83.2	255	79.4	131	8.5 * 8.8	48	12.2	62	8.1	19	5.9	11.0	84	7.0	47	3.9
Laboratory data mngmt. systems	508	33.1 *30.1	117	29.7	269	35.3	106	32.7	217	14.1 *18.4	52	13.2	98	12.9	48	14.8	42.7	76	14.9	177	81.6
Laboratory furnaces, ovens	1,118	72.6 *69.9	283	71.8	596	78.3	196	61.7	117	7.6 * 7.5	47	11.9	53	7.0	16	5.0	10.5	87	7.8	30	2.7
Microscopes, electron	273	17.7 *19.0	101	25.6	114	15.0	50	15.6	47	3.1 * 2.9	19	4.8	18	2.4	12	3.7	17.2	12	4.4	35	12.8
Microscopes, optical	1,021	66.3 *64.9	280	71.1	466	61.2	241	75.1	97	6.3 * 6.9	33	8.4	37	4.9	24	7.5	9.5	69	6.9	37	3.6
Nuclear magnetic resonance equip.	156	10.1 *10.1	23	5.8	112	14.7	16	5.0	36	2.3 * 2.9	4	1.0	25	3.3	6	1.9	23.1	14	9.0	22	14.1
pH meters	1,094	71.1 *71.7	210	53.3	553	72.7	288	89.7	106	6.9 * 7.7	22	5.6	53	7.0	27	8.4	9.7	89	8.1	17	1.6
Recorders, strip chart	1,045	67.9 *68.9	280	71.1	531	69.8	197	61.4	105	6.8 * 7.2	47	11.9	41	5.4	12	3.7	10.0	70	6.7	35	3.3
Recorders, x-y plotting	596	38.7 *37.7	195	49.5	295	38.8	85	26.5	105	6.8 * 5.9	49	12.4	41	5.4	13	4.0	17.6	44	7.4	61	10.2
Specific ion electrodes	480	31.2 *31.7	71	18.0	268	35.2	134	41.4	65	4.2 * 6.4	13	3.3	46	6.1	10	3.1	13.7	94	11.5	41	8.6
Spectrometers, electron	52	3.4 * 4.4	18	4.6	25	3.3	7	2.2	9	0.6 * 1.2	3	0.8	5	0.7	1	0.3	17.3	5	5.6	6	11.5
Spectrometers, mass	161	11.6 *13.0	49	12.4	111	14.6	17	5.3	36	2.3 * 2.9	10	2.5	18	2.4	7	2.2	18.9	17	9.4	19	10.5
Spectrometers, plasma, dc	34	2.2 * 1.1	6	1.5	25	3.3	2	0.6	8	0.5 * 1.1	3	0.8	5	0.7	—	—	23.5	—	—	8	23.5
Spectrometers, plasma, ICP	62	4.0 * 4.8	9	2.3	48	6.3	2	0.6	30	1.9 * 2.9	7	1.8	22	2.9	1	0.3	48.4	4	6.5	26	41.9
Spectrometers, x ray	188	12.2 *12.1	51	12.9	124	16.3	6	1.9	26	1.7 * 2.3	7	1.8	17	2.2	1	0.3	13.8	8	4.3	18	9.6
Spectrophotometers, atomic abs.	383	24.9 *27.6	55	14.0	265	34.8	49	15.3	29	1.9 * 3.4	3	0.8	21	2.8	5	1.6	7.6	10	2.6	10	5.0
Spectrophotometers, fluorescence	197	12.8 *13.2	26	6.6	90	11.8	74	23.1	22	1.4 * 2.4	1	0.3	7	0.9	13	4.0	11.2	4	2.0	18	9.1
Spectrophotometers, FTIR	149	9.7 * 8.6	25	6.3	115	15.1	7	2.2	39	2.5 * 5.1	14	3.6	21	2.7	4	1.2	26.2	4	16.1	7	4.7
Spectrophotometers, infrared	436	28.3 *33.6	61	15.5	316	41.5	45	14.0	44	2.9 * 3.6	11	2.8	27	3.6	6	1.9	10.1	18	4.3	25	5.7
Spectrophotometers, UV/vis	645	41.9 *45.3	59	15.0	372	48.9	191	59.5	67	4.4 * 5.7	8	2.0	37	4.9	22	6.9	10.4	28	5.9	29	4.5
Titrators, automatic	291	18.9 *17.5	47	11.9	192	25.2	42	13.1	71	4.6 * 5.3	8	2.0	40	5.3	18	5.6	24.4	18	6.3	52	17.9
Other	149	9.7 * 7.8	30	7.6	76	10.2	34	10.6	52	3.4 * 3.5	16	4.1	20	2.6	14	4.4	34.9	28	16.8	24	16.1

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ABOUT THE COVER

The cover photo was made through a port in the door of a Denton Vacuum DVB-44 box coater. The CC-101B ion source was operating in an oxygen atmosphere for ion-assisted deposition.

All light comes from the unit itself, with no outside light source. This is, perhaps, the first time that the actual electron path has been made visible. The ionized cloud also can be seen in the photo.

Additional vacuum information is in the Vacuum Technology section beginning on p 105.

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CHANGE CHARACTERIZES R&D AS INDUSTRY ENTERS 1986

Survey shows that shifts have occurred in rates of salary increases, years of experience, and balance of academic achievement, completely rearranging our industry profile.

Robert R. Jones, Editor

THE R&D INDUSTRY is more noted for change than stability, but the past 12 months in research, development, and quality assurance have been months of unusual flux.

Shifts have occurred in national and international manufacturing and marketing patterns, in corporate structures, in company ownerships, in product lines, in starting salaries, in retirement programs, and in other important features of this industry with a resulting low-level but very real impact for research and development on who is doing what for whom and for what rewards.

Despite all of the changes, this year's annual profile of our industry brings good news for most workers. Salaries remain good, largely advancing faster than inflation, and indicators point to a substantial body of new workers joining the industry.

We present here the first of a two-part report based on our annual survey of workers' salaries and related rewards in research, development, and quality assurance. This article deals, for the most part, with the total survey population of more than 3,600 respondents.

As was mentioned in last year's report, our salary survey scale was established in the early years of this annual study with $3,000 spans—$16,000 through $18,000, $19,000 through $21,000, etc. In the years when our top income figure was below $50,000 this was easy to handle.

However, as we added a span or two each year and reached $70,000, the number of spans became burdensome and charts became needlessly complex.

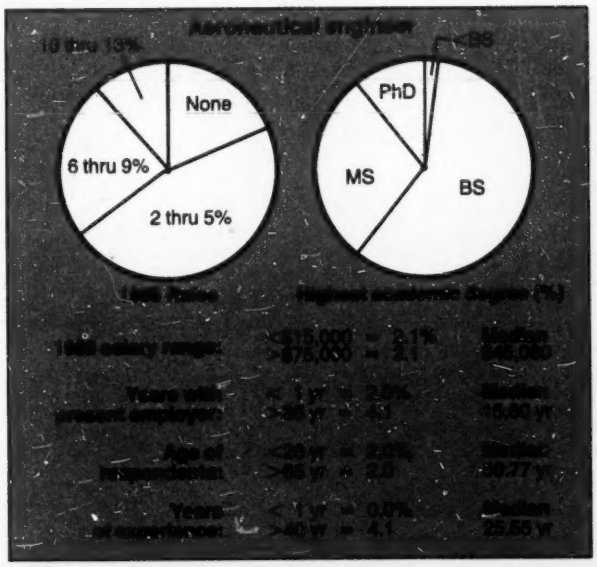
Last year we made a break, realizing that to do so would interrupt the easy comparison of year-to-year changes. Now the spans cover $5,000, *e.g.*, $15,000 through $19,000.

Part of the above problem lay in the fact that while the top end of the range for workers in research, development, and quality assurance moved steadily upward, the bottom end seemed permanently fixed somewhere below $15,000.

Then, it was first noted two years ago that the total salary range finally appeared to be moving upward. While this year still finds nearly one percent (0.9%) of the respondents in the "less than $15,000" salary range, this is down from 1.6% last year.

The number at the upper end ($75,000 per year or more) has increased since last year by about the same amount, from 1.5% of the repondents to 2.0%.

With two out of every 100 workers in R&D earning $75,000 a year or more, it is hard to believe that just six years ago the upper range in our survey was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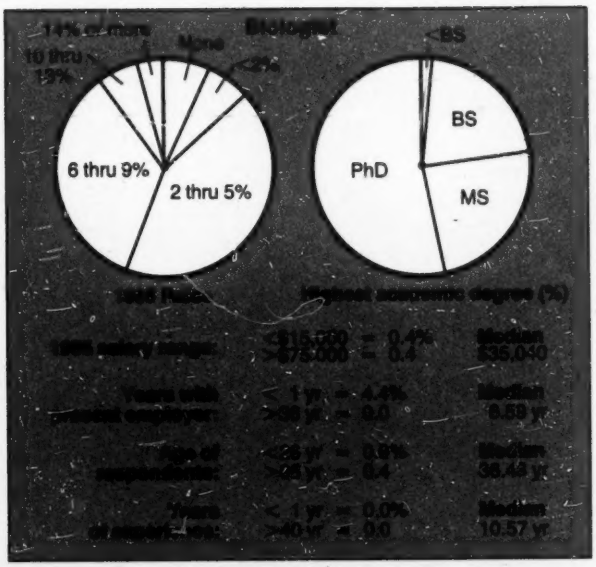
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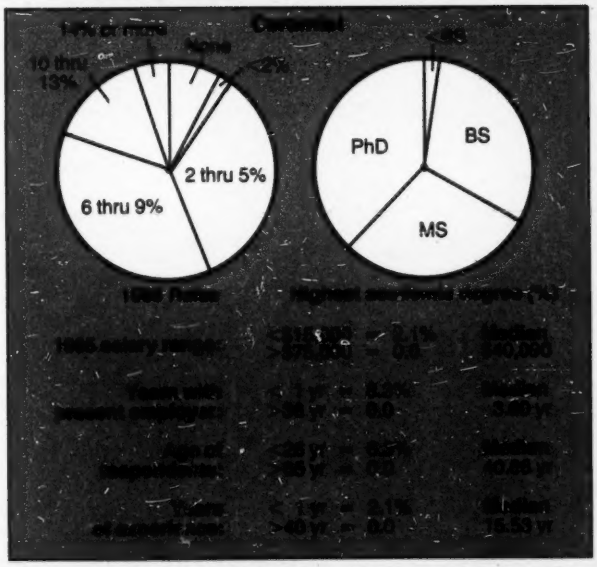
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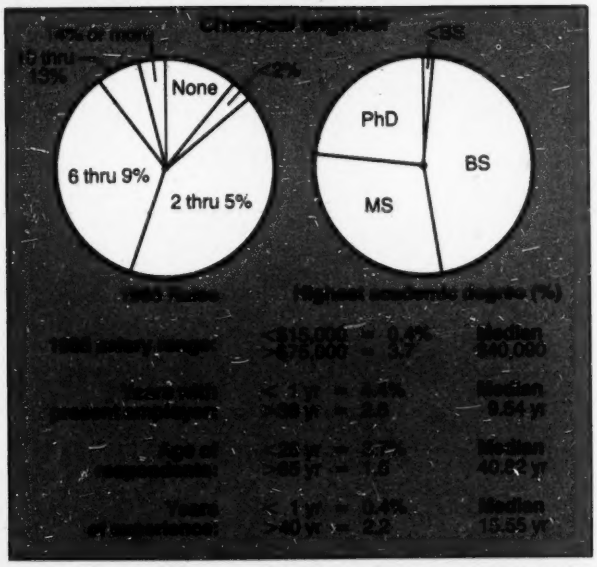
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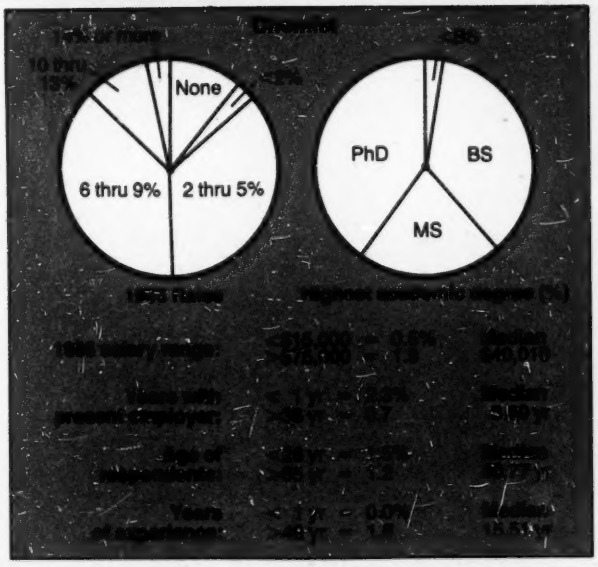
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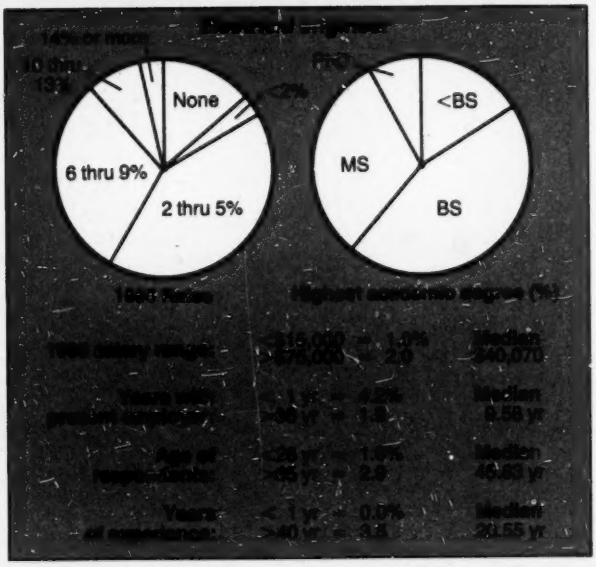
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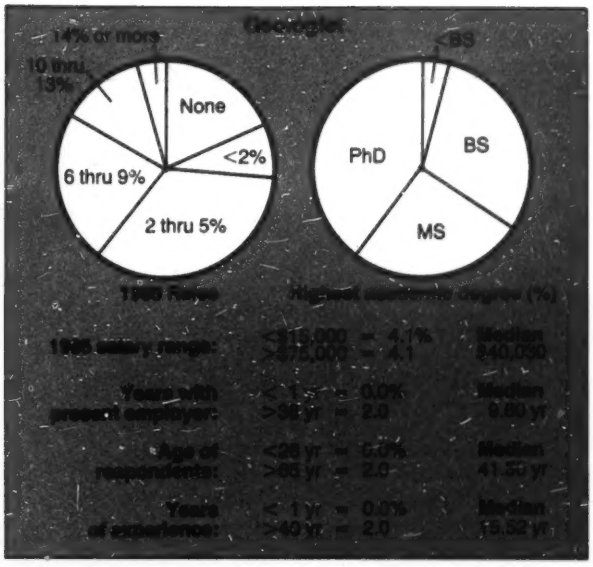
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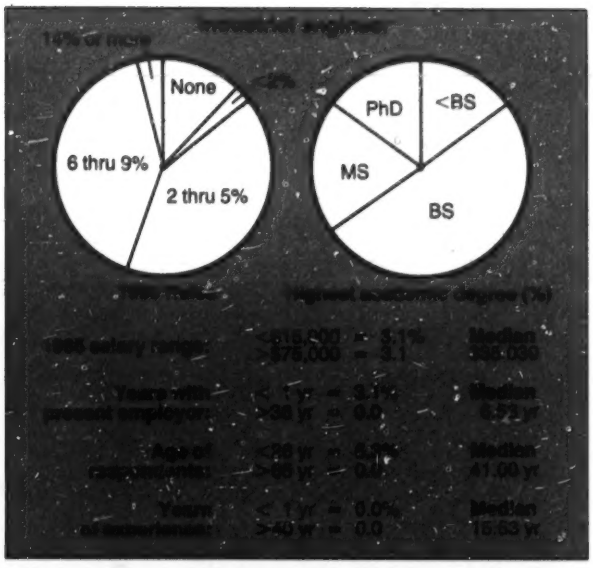
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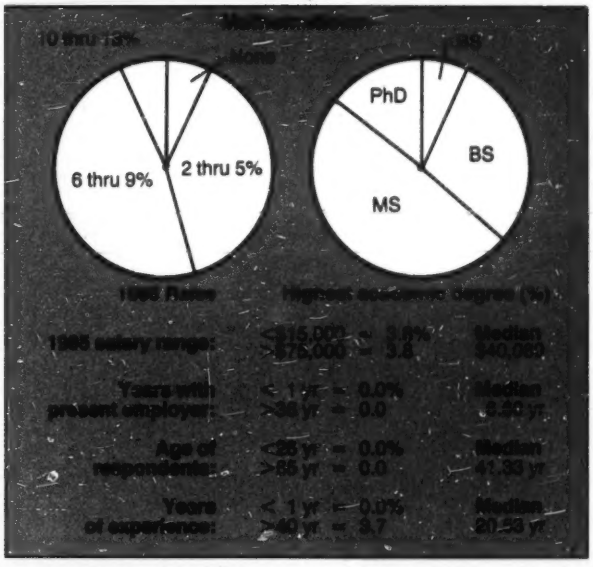
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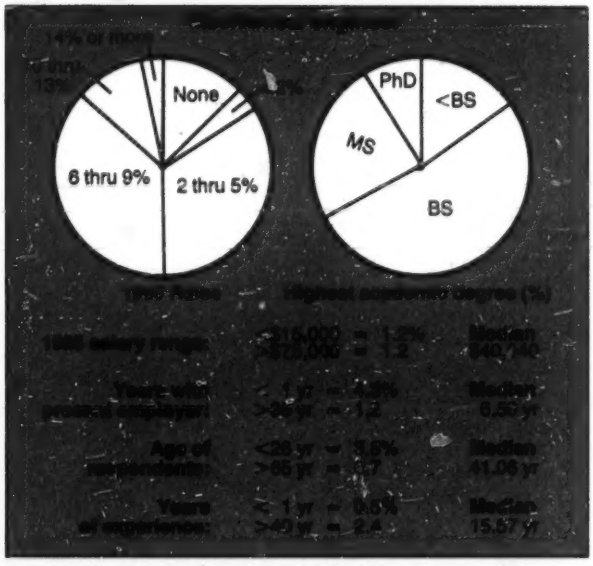
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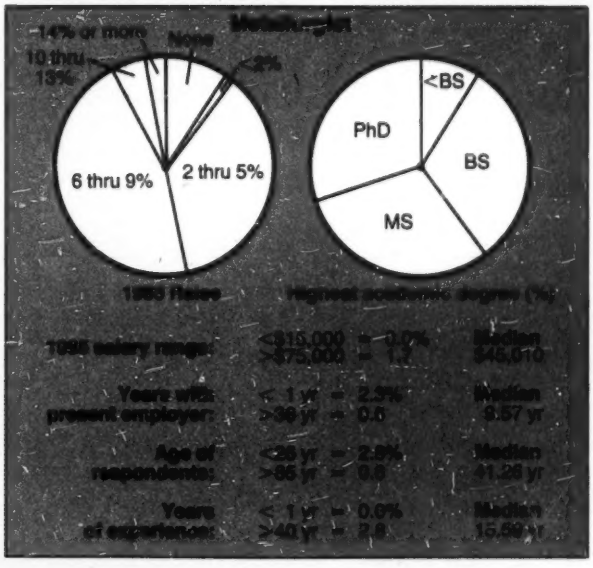
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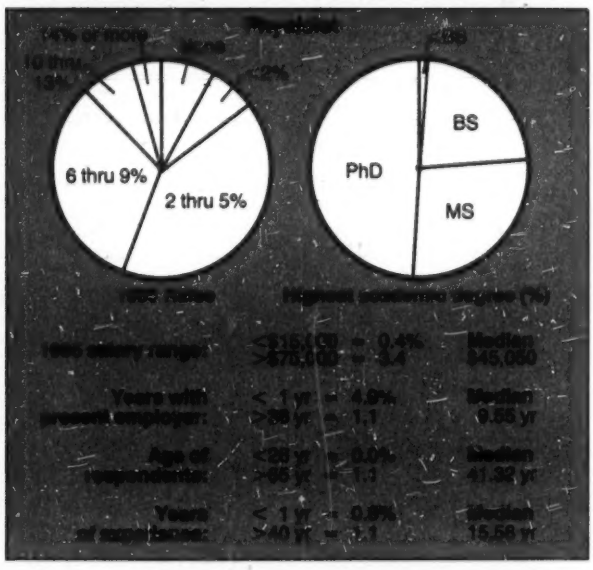
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$46,000. At that time the bulk of the respondents fell into the $25,000 through $27,000 category.

Salary increases this year are smaller than in some recent years, but we continue to enjoy low inflation rates, with one result being that the portion of respondents' raises which exceed the rate of inflation stays about the same.

Increases in rate of pay

	% of respondents				
Amount	1986	1985	1984	1983	1982
None	11.3	9.3	16.3	14.7	6.3
Less than 2%	3.6	2.9	2.1	1.9	1.2
2 through 5%	37.1	36.6	26.9	15.9	10.6
6 through 9%	36.3	37.6	38.9	34.2	34.5
10 through 13%	8.3	10.1	11.5	25.1	34.0
14% or more	3.3	3.6	4.4	8.2	13.3
Ahead of inflation	60.1	63.3	54.8	33.4	47.3

Once again buying power has increased for R&D workers as a group, with 3 out of 5 getting salary increases that do more than just stay even with inflation. This is true even though the percentages in the upper salary increase levels are much lower than they were in the early part of the 1980s.

The percentage receiving no salary increase for this year is up from last year, but still well below the figures for 1983 and 1984. And the no-increase group always includes a number of new-hires.

The most impressive salary increase performance again came from the ceramists with 55.4% getting increases of 6% or more last year. In our previous report they led with 60% in this category. Mathematicians follow the ceramists with 53.9% getting raises of 6% or more last year; 53.5% of the metallurgists got such raises, as did 50.2% of the chemists. Geologists were displaced from the low end by aeronautical engineers with only 37.5% of the latter getting increases of 6% or better last year.

One result of these increases is to make workers in research, development, and quality assurance an affluent demographic segment. For this group, the paychecks in 1986 will total $24.5 billion. This can be compared to $18.9 billion just two years ago.

Rankings for disciplines by median salaries

Rank			Median salary		
1986	1985	Discipline	1986	1985	% increase
1	3	Metallurgist	$49,166	$44,580	10.3
2	2	Aero. Engr.	48,181	49,330	−2.3
3	5	Physicist	47,426	43,120	9.9
4	7	Chem. Engr.	44,619	42,390	5.3
5	4	Ceramist	44,285	43,450	1.9
6	1	Mathematician	44,166	51,200	−13.7
7	8	Elec. Engr.	43,291	42,910	0.9
8	6	Mech. Engr.	41,901	42,180	−0.7
9	9	Geologist	41,136	41,830	−1.7
10	10	Chemist	40,295	39,040	3.2
11	13	Biologist	37,013	34,960	5.9
12	11	Indust. Engr.	36,696	38,280	−4.2
13	12	Other	35,194	35,190	2.8

The median salary for all respondents in this study is $41,449, up 3.2% from last year's $40,180.

Looking at median salaries by disciplines, we see that mathematicians fell substantially from their leadership position of last year to be replaced this year by metallurgists. This is explained, in part, by the fact that the largest gain in median salary was made by metallurgists with 10.3%. Physicists were next at 9.9, followed by biologists at 5.9%.

This brings up the question of how there can be the salary increases that we mentioned above and at the same time have declines in median salaries. This, we must concede, could be a result of sampling error. However, this study has appeared to escape such sampling glitches in the past, and the number of respondents remains good for conclusions based on the total population.

At the same time, as mentioned earlier, there are indications in other portions of the study that early retirement programs, which have been fairly common in U.S. industry this past year, may be having an impact on our results. This shows up in our reports on years of experience, years with present employer, and median age of respondents.

There continues to be a premium on age, experience and advanced degrees in research and development, but the scale has been shifted. Where previously the median age of our respondents had moved steadily upward beginning in 1980 with 40.4 years followed by 40.9, 40.9, 41.4, 41.5, and 42.0, this year's median age is once again 40.9 years.

Likewise, the median years of experience of our respondents has increased in recent studies from 15.8 in 1982 to 16.5 in 1985. This year it is 15.5 years.

When salary is correlated to experience, the premium that is paid for experience remains obvious, despite the downward shift in the scale. For this year's respondents with less than one year's experience, the median income is $24,375, compared to $27,020 last year. Median income for those with one through five years of experience is $31,957, up from $30,380. For six through 10 it is $35,596 compared to last year's $35,030.

At the upper end of the experience range, those with 36 through 40 years' experience have a median income of $48,321 this year, compared to $46,967 last year.

The percentage of respondents with PhD degress has moved from 27.6 in 1980 with only one hesitation to 33.1% in 1985. This latest study places the figure at 30.1%, once again suggesting that the top end of the R&D work force has been lopped off by early retirement programs.

Biologists lead the field with the most respondents having PhDs at 54.1%. When masters and doctorates are considered together and disciplines are ranked for advanced degrees, biologists continue to lead with 78.1%, followed by physicists at 76.0, ceramists 66.7, and geologists 66.0.

In the second part of this report we will look into the implications of some of the above conclusions and also report on the value os advanced degrees in this recently-modified world of research and development. We also will examine relative pay scales for men and women, and the advantages in salaries for jobs in industry, government, and universities. R&D

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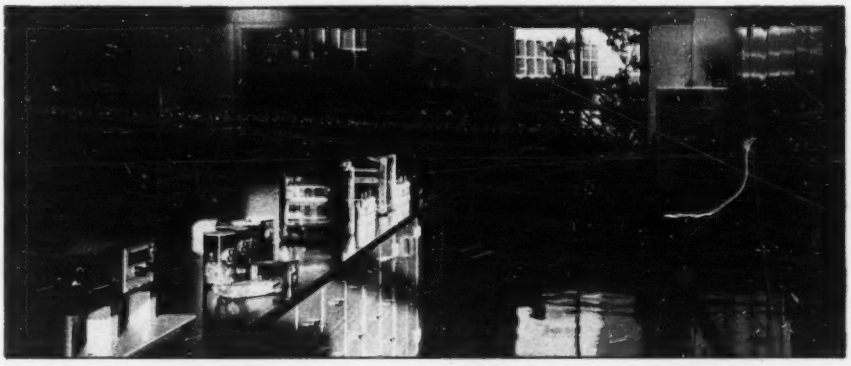
Natural light reaches into labs. **See p 74.**



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ABOUT THE COVER

R&D's 1986 Lab of the Year, the Robert M. Schaeberle Technology Center of Nabisco Brands Inc. at East Hanover, NJ, is a place of contrasts. The laboratory's designers had to provide a people-oriented structure that would further creativity. At the same time, the lab had to be functional and efficient. The project had to be completed as quickly as possible.

The Lab-of-the-Year judges also awarded High Honors to the Monsanto Research Center at Chesterfield, MO.

An article describing the Lab of the Year and the High Honors Lab begins on p 74.

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R&D industry has younger, leaner look for days ahead

Belt-tightening changes in employment practices appear to be major factors in new shape for industry profile; women continue to make gains relative to men as median salary levels decline.

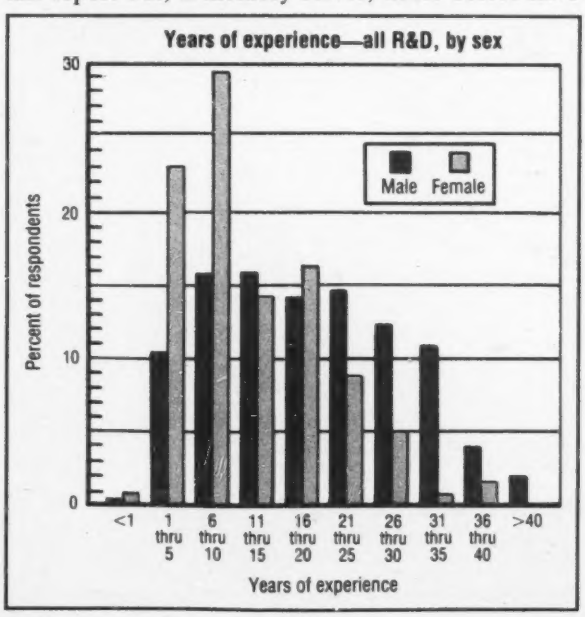
Robert R. Jones, Editor

THE PAY SCALE in industrial R&D has taken some lumps in the recent economic slump, and has pulled the median salary for all R&D down with it. At $40,030 per year, the median for all R&D workers in all types of workplace is down 0.4% from last year's $40,180, if the more than 3,600 respondents to this survey are representative of research and development.

While there are no drastic differences in our industry profile from last year's report, there are small dips in a number of indicators. Occasional dips have been routine in the nearly 15 years that we have been writing this report but, if memory serves, never before have there been so many in one year.

The median salaries for workers in government and universities rose during the past year, but not enough to offset the decline in industry. This and a number of other changes for workers in research and development would appear to be direct results of changes in employment policies which have encouraged early retirement on the one hand and have led to reduced hiring on the other.

Even with a decline last year in place of the usual increase, median salaries for R&D in 1986 remain close to what inflation would have done to 1980 salaries. Thus, R&D workers' buying power has held up.



Median salaries all R&D by workplace

	1980	1985	1986
Government	$29,733	$39,790	$40,020
Industry	28,354	40,980	40,040
University	25,685	34,950	35,030

With cutbacks at both ends of the employment range, the middle has become stronger. This is apparent when we compare salary and educational achievement. R&D workers whose top academic degree is a master's fit mid-range in the salary scale. And, consistent with the above, they are the only ones in that comparison table whose salaries increased last year.

In the same period, the percentage of respondents with master degrees declined only 1.6% while the percentage of PhDs fell by 9.1%. Those early retirement programs could be expected to remove some of the highest paid PhDs from a research staff.

And we find that the spread in career earnings for a PhD over a master degree has declined sharply this year after having climbed for several years. Last year's spread was $470,000, up $100,000 from a year earlier.

This year the spread has declined to $340,000, down 27.7% in one year and 8.1% below the spread of two years ago.

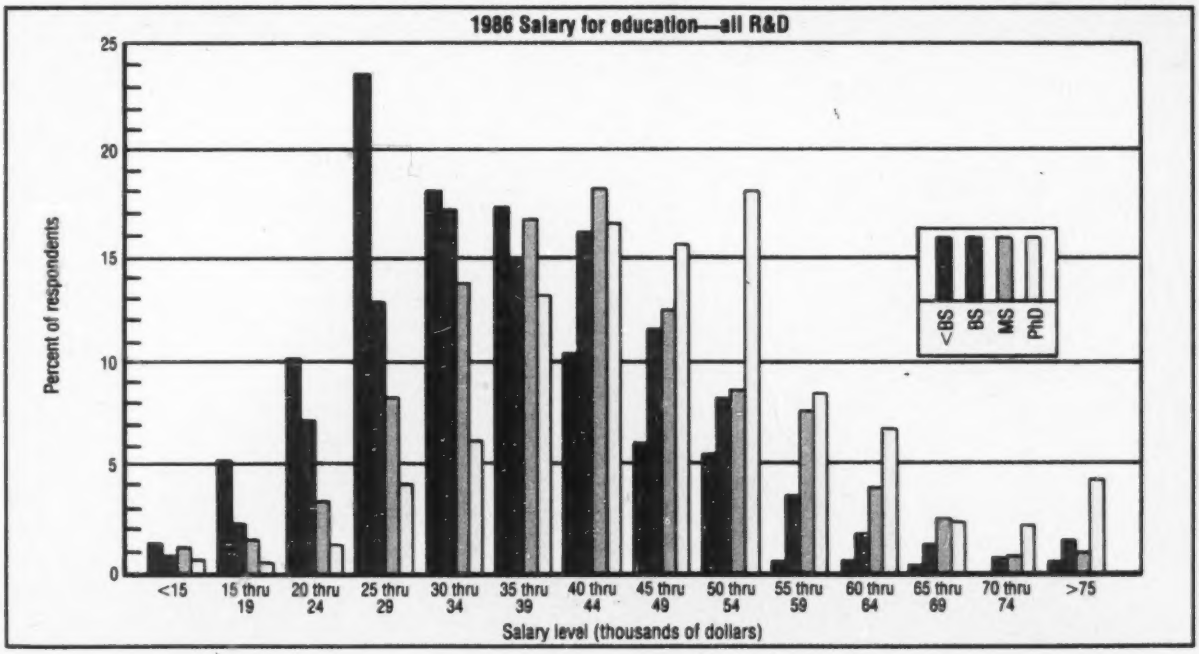
But the master degree was the exception in the academic comparisons. The advantage of a PhD over a baccalaureate degree increased 9.9% to $780,000 compared to last year's $715,000. This is based on a 25-year working career for the PhD, with interest figured at 10% and $300,000 allowed for tuition, missed earnings, etc.

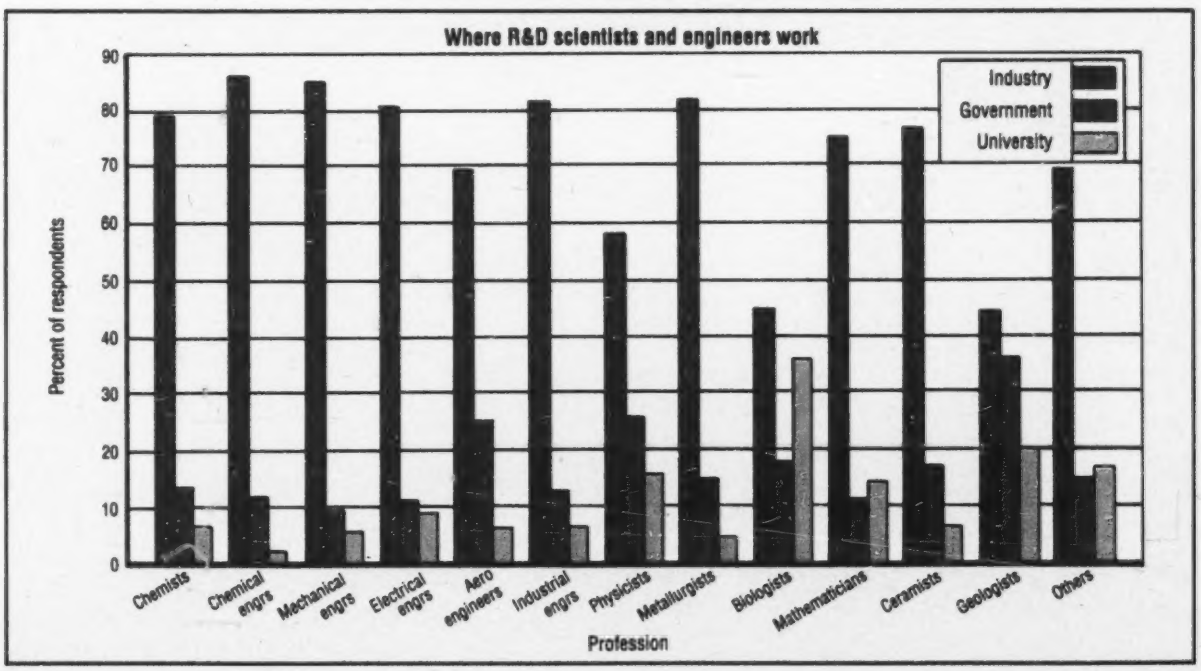
With 5.6% of our respondents reporting more than 35 years' experience, it is not inconceivable that some PhDs will have a 35-year career. Those who do could expect to reap a $2,678,000 career advantage over the person whose education stops after a BS, because the later years of the career are where the income difference is most striking.

If you know someone who is wondering about the advantage of college education at all, the answer is that it is real, and that it increased during the past year at a rate greater than the rate of inflation.

The benefit for a BS over less than BS now is $590,000, up nearly 4.5% from last year. This means that—after adjustments for tuition and other factors—those four years invested in a college education will return $147,000 for each of those years.

Going on to get an MS is worth even more this year, what with the above-mentioned shift in the relative value of a master degree in the salary comparison. This year, adding the MS to a BS is worth $437,000





over a 25-year career, or $17,500 more income during each of those career years.

At the extreme end of the comparison, getting a PhD over not having any degree could be worth $1,173,000, up 7.4% from last year and 34.1% from two years ago. That works out to an average of $3,900 more in the pay check *each month* over a 25-year career.

Additional information and comparisons may be derived from the following summation:

R&D salaries compared by academic degrees

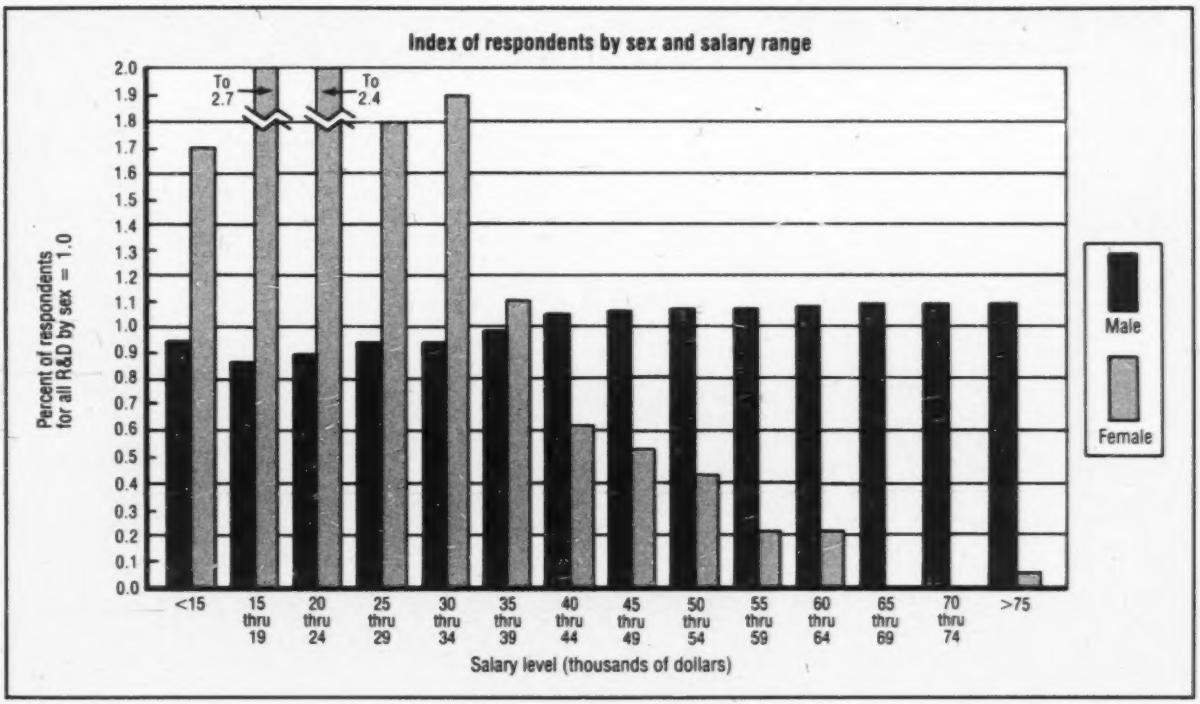
Degree	Median salary 1986	Median salary 1985	Percent change	Annual difference* 1986	Annual difference* 1985	Difference Increase (percent)
Doctorate	$45,050	$45,720	−1.4	$5,020	$6,200	−19.0
Master	40,030	39,520	+1.3	4,970	3,180	+56.3
Bachelor	35,060	36,340	−3.5	5,010	4,870	+ 2.9
<Bachelor	30,050	31,470	−4.5			

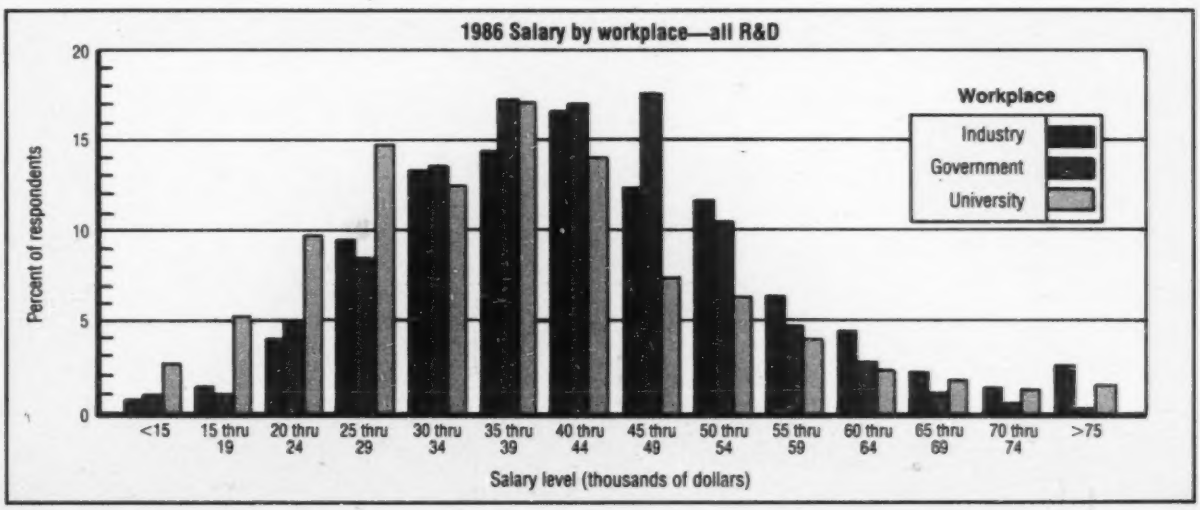
*Difference above next lower degree

Information obtained in this study makes it clear that the net value of any degree depends on the individual degree holder's field of endeavor and sex; whether the employer is from industry, university, or government; and the individual's skills and performance. In addition, it should be remembered that the figures derived above are from salary medians, and obviously some individuals will be above and others below these figures, regardless of academic degrees.

As regards sex differences in salaries, we have pointed out for a number of years that women who work in research, development, and quality assurance do not earn as much as men do. In too many instances, it is a result of discrimination, but there are valid reasons in some other instances of lower salaries for women.

Our typical female respondent will have less experience and less time with her present employer, and is less likely to have an advanced degree than is the typi-





cal male. All of these have important bearing on the size of the salary.

As an example, the median income for male R&D workers in industry is $40,050, a figure that can be contrasted with the median for females in industry, $30,070, or females in universities, $25,100.

Despite the fact that women in universities were the only group whose median rose last year over the year before, they still rank at the bottom of the list. And despite all of the gains that women have made in salaries, the highest female median still falls almost $5,000 per year below the lowest for males. The rankings are as follows:

	1986	1985	% gain
Men in industry	$40,050	$41,750	−4.1
Men in government	40,040	40,400	−0.9
Men in universities	35,040	36,040	−2.6
Women in industry	30,070	31,590	−4.8
Women in government	30,040	33,130	−9.3
Women in universities	25,100	24,040	+4.4

In this year's survey, the median annual income for all males is $40,040, down 2.2% from $40,990 last year but still above the $38,440 of two years ago. For all females, it is $30,060, down 3.4% from last year's $31,130, but still well above a year earlier's $28,990.

Over recent years we have said more than once that women are making gains in the effort to get equal pay for equal work. This year's study shows that women did far better than men in terms of salary increases. While 52.8% of the men got no increase or increases of less than 6%, only 42.5% of the women were in that group. Fully 42.8% of the women respondents reported salary increases of 6 through 9%, and 14.7% reported increases of 10% or more.

R&D salary increases by sex

Amount	1984 % Male	1984 % Female	1985 % Male	1985 % Female
None	9.4	8.6	11.6	7.7
Less than 2%	2.8	3.7	3.6	3.5
2 through 5%	36.6	35.2	37.6	31.3
6 through 9%	37.8	34.5	35.8	42.8
10 through 13%	9.8	14.6	8.3	8.9
14% or more	3.6	3.4	3.1	5.8

Of the women respondents this year, 64.9% report that they are earning more than $30,000 per year, up from 56.6% last year, a 14.6% increase. Of the men, 84.2% report annual salaries of more than $30,000 per year, up from 80.4% last year, a 4.7% increase. Again, salaries for women are moving closer to those for men.

This and other information about comparable salaries is conveyed in a newly designed chart which presents income in each salary range for each sex on an index basis. Inasmuch as 92.8% of this year's respondents are male, and if all else were equal, 92.8% of the workers in each salary range would be males and 7.2% female. Thus, the chart indicates 1.0 for ranges where the percentage of males is 92.8. If only half that percentage of males is in that range, the index for males is 0.5.

On the chart showing years of experience by sex, it

1986 R&D Industry profile:

1. What is your annual salary?
   a. Less than $15,000 ..... 0.9%
   b. $15,000 to $19,999 ..... 1.7
   c. $20,000 to $24,999 ..... 4.7
   d. $25,000 to $29,999 ..... 9.9
   e. $30,000 to $34,999 ..... 13.1
   f. $35,000 to $39,999 ..... 15.1
   g. $40,000 to $44,999 ..... 16.5
   h. $45,000 to $49,999 ..... 12.5
   i. $50,000 to $54,999 ..... 10.9
   j. $55,000 to $59,999 ..... 5.8
   k. $60,000 to $64,999 ..... 3.7
   m. $65,000 to $69,999 ..... 1.9
   n. $70,000 to $74,999 ..... 1.1
   o. $75,000 or more..... 2.0

2. Your raise during the past year was
   a. None..... 11.3%
   b. Less than 2% 3.6
   c. 2% through 5% 37.1
   d. 6% through 9% 36.3
   e. 10% through 13% 8.3
   f. 14% or more 3.3

3. How long have you worked for your present employer?
   a. Less than 1 year 3.4%
   b. 1 through 3 years 14.7
   c. 4 through 6 years 17.9
   d. 7 through 9 years 13.8
   e. 10 through 12 years 9.1
   f. 13 through 15 years 6.9
   g. 16 through 18 years 8.3
   h. 19 through 21 years 6.7
   i. 22 through 24 years 6.3
   j. 25 through 27 years 4.4
   k. 28 through 30 years 3.5
   m. 31 through 33 years 2.3
   n. 34 through 36 years 1.6
   o. More than 36 years..... 1.1

4. What is your age?
   a. Under 26 years..... 2.0%
   b. 26 through 30..... 9.5
   c. 31 through 35..... 15.1
   d. 36 through 40..... 16.5
   e. 41 through 45..... 15.7
   f. 46 through 50..... 13.1
   g. 51 through 55..... 12.0
   h. 56 through 60..... 9.3
   i. 61 through 65..... 5.6
   j. Over 65 years..... 1.2

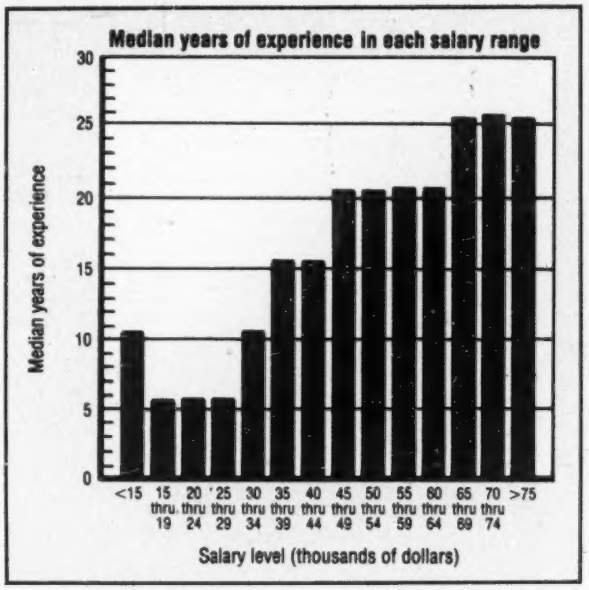
5. How many years of experience do you have?
   a. Less than 1 year 0.2%
   b. 1 through 5 years 11.3
   c. 6 through 10 years 16.7
   d. 11 through 15 years 15.7
   e. 16 through 20 years 14.3
   f. 21 through 25 years 14.3
   g. 26 through 30 years 11.7
   h. 31 through 35 years 10.1
   i. 36 through 40 years 3.9
   j. More than 40 years..... 1.7

6. What is the highest degree you hold?
   a. Less than bachelor..... 8.2%
   b. Bachelor 36.6
   c. Master 25.2
   d. Doctorate 30.1

7. What is your profession?
   a. Chemist..... 37.1%
   b. Chemical engineer 7.5
   c. Mechanical engineer ... 11.6
   d. Electrical engineer 8.6
   e. Aeronautical engineer... 1.4
   f. Industrial engineer 0.9
   g. Physicist 7.3
   h. Metallurgist..... 4.9
   i. Biologist 6.3
   j. Mathematician 0.7
   k. Ceramist 1.3
   m. Geologist..... 1.4
   n. Other 10.9

8. Do you work in
   a. Industry..... 75.3%
   b. Government..... 14.6
   c. University 10.1

9. Are you
   a. Male 92.8%
   b. Female..... 7.2



is obvious that there is a large body of experienced males in R&D, with 40.2% having more than 20 years' experience. Even though this is down from 41.5% last year, it still is far ahead of the women's figure of 17.0% with 20 years' experience, despite the fact that the latter figure is up from 15.9% last year.

One cannot have long experience while young, and a large portion of the female workers, 68.4%, are younger than 40 years of age. Only 41.3% of the men are that young.

One result of the relative youth of the females is that few have PhDs. The percentage with PhDs in this year's respondents is 20.4, up from 19.1 last year and 14.8 two years ago. For this year's male respondents, the figure is 30.7%, down from 34.4% last year and also down from close to 32% for the preceding several years.

Time spent with the same employer often is reflected in higher salary. The fact that 5.2% of the male respondents have been with their present employers for more than 30 years helps to explain the males' higher positions in the organization and on the salary scale. Even though this figure is down from 5.9% last year, it still is far above the 1.2% for females for both years.

For many reasons women are unable to stay with a single employer as long as men are. This puts a large number of females in the short-term brackets. This year, 53.5% report having less than seven years with their present employer. Only 34.7% of the males have been with their present employer less than seven years.

As you study these charts and tables and make comparisons with previous years, you will find a substantial number of clues to the changes that we mentioned in our opening comments. More often than not, the median or the upper range in industry has declined slightly, and this has pulled the whole scale down, because industry dominates R&D in the U.S.

One result is that the entire profile of R&D has been changed. It will be another year before we can say whether this begins a trend that reflects changed employment practices, or merely is a glitch or a transient in our data. R&D

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CIRCLE 162 ON INQUIRY CARD

OPINION POLL RESULTS

Readers tilt cautiously toward R&D contracting

READER OPINION on the subject of contract research has changed noticeably since 1973. While they stop far short of endorsing the use of contracts as a standard approach to research and development, the nearly 600 respondents to this survey are much more willing to accept the idea than they or their counterparts were 13 years ago.

And, along with those changes, opinions on other questions are virtually identical to the opinions expressed in 1973. The same questions were asked in both surveys.

Reader evaluation of the desirability of traditional grant procedures from the standpoints of science and of mankind differ by only a few percentage points in the two surveys.

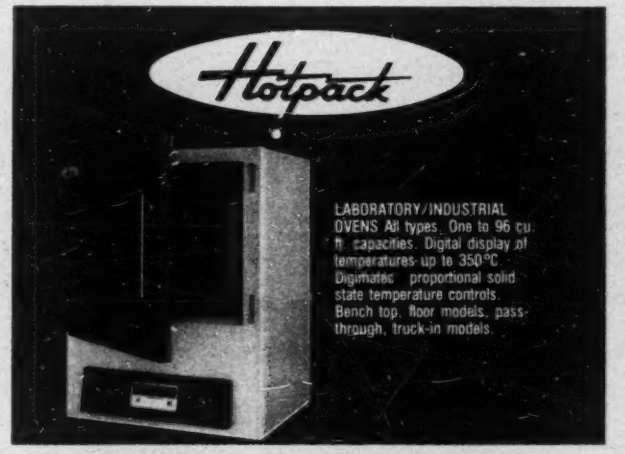
The same is true for having research needs evaluated for funding purposes by a board of scientists selected for that purpose (an idea that was being pushed in 1973), by NSF, or by Congress.

Among the changes, the response to "Does it seem to you that grants should be eliminated by funding agencies in favor of contracts designed to achieve efficiency in research?" changed from 22% voting *Yes* or *Yes, mostly* to 32%.

Those who feel that contract research has gone too far dropped from 1973's 47% to 28%. And the portion favoring a policy statement against research contracts declined from 35% to 17%.

Complete results of the two surveys follow:

	1986	1973
1. Do you feel that traditional grant procedures have been desirable for science?		
a. Yes, definitely	22%	24%
b. Yes, generally	45	49
c. Neutral	13	8
d. I doubt it	13	12
e. Definitely not	4	5
f. No opinion on this	3	2
2. Do you feel that traditional grant procedures have been desirable for mankind?		
a. Yes, definitely	21%	20%
b. Yes, generally	45	50
c. Neutral	15	11
d. I doubt it	12	13
e. Definitely not	4	5
f. No opinion on this	3	1
3. Does it seem to you that contracts for research make the most sense when there are recognized and specific needs?		
a. Yes	49%	39%
b. Yes, but . . .	39	49
c. No	10	11
d. No opinion on this	2	1
	1986	**1973**
4. Does it seem to you that grants should be eliminated by funding agencies in favor of contracts designed to achieve efficiency in research?		
a. Yes	14%	11%
b. Yes, mostly	18	11
c. Sometimes	40	41
d. No	28	37
5. Should the research needs be rated for priority by a top scientist or group such as NSF, and contracted accordingly?		
a. Yes	52%	50%
b. No	48	50
6. Should research needs be rated by Congress or other non-scientific group, and so contracted?		
a. Yes	8%	9%
b. No	92	91
7. Has contracting gone too far, already?		
a. Yes	28%	47%
b. No	72	53
8. Do you favor a policy statement against contracts?		
a. Yes	17%	35%
b. No	83	65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CIRCLE 101 ON INQUIRY CARD

OPINION POLL RESULTS

Revise shuttle program; save money and lives

READERS of *Research & Development* believe that the U.S. should revise the space program to use unmanned space probes so as to save money and not endanger human lives.

That opinion may not seem surprising in the aftermath of the *Challenger* tragedy, but this response from readers came in Opinion Poll responses which were mailed to us *before* January 28. Even before *Challenger* fell, two out of three *R&D* readers believed that the time had come for NASA to make major changes.

The response was among those to a series of questions which first were included in our Opinion Poll Questionnaire in 1972, and then were repeated for comparison purposes last summer. Numbers of respondents to the surveys were almost identical: 2,236 in 1972 and 2,279 in 1985.

And, to the extent that these respondents are typical of the R&D community, some very interesting similarities have survived those 13 years—and there also are some, possibly significant, changes in opinion.

One change is a substantial increase in the number who favor additional funding for the space program, up from 49% of respondents in 1972 to 66% in 1985.

In the matter of alternative uses for space funds, those who favored alternatives in 1972 rated eradication of poverty, control of pollution, and exploitation of the oceans far higher than did 1985 respondents. The latter put a heavy emphasis on expanding basic research as an alternative to space flights.

Complete results of the surveys follow:

	1985	1972
1. Do you feel that the amount of money spent on the space program should be:		
a. Increased	66%	49%
b. Decreased	8	19
c. Continued at its present level	26	32
2. If you think our efforts in space should be maintained, which one of the following do you favor?		
a. Exploration and scientific colonization of the moon	20%	17%
b. Unmanned probes to nearby planets	12	*
c. Manned missions to nearby planets	16	17
d. Orbiting laboratories	52	37
* Question not phrased the same in 1972.		
3. If you feel that the money and manpower now being devoted to space exploration should be marked for more-Earthly projects, which of the following do you favor?		
a. Strengthen national defense	10%	8%
b. Exploit the oceans	15	20
c. Eradicate poverty	12	17
d. Control pollution	19	27
e. Expand basic research	38	23
f. Other	5	5
4. With a properly formulated exploration program, should we use unmanned space probes so as to save money and not endanger human lives?		
a. Yes	64%	41%
b. No	36	59
5. Considering the many side benefits claimed by supporters of the space program, should its continuance be directly related to these developments?		
a. Yes	38%	38%
b. No	62	62
6. Do you believe that the U.S. and Russia should work in a joint effort toward a cooperative space station as well as other combined ventures?		
a. Yes	60%	85%
b. No	40	15
7. Do you think that results from space experiments could further your particular R&D efforts?		
a. Significantly	26%	24%
b. Slightly	50	48
c. Not at all	24	28
8. Do you feel that rocket launchings and injection of satellites into orbit are causing undesirable changes in the atmosphere?		
a. Yes	8%	17%
b. No	92	83

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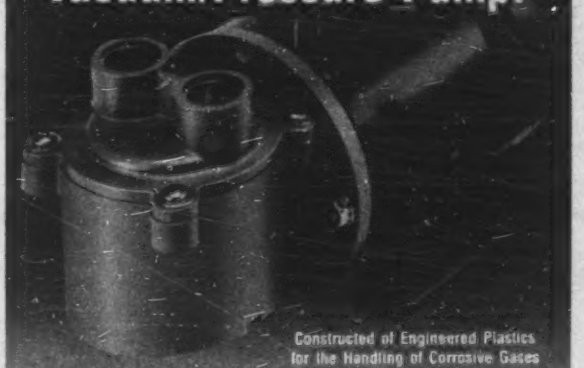

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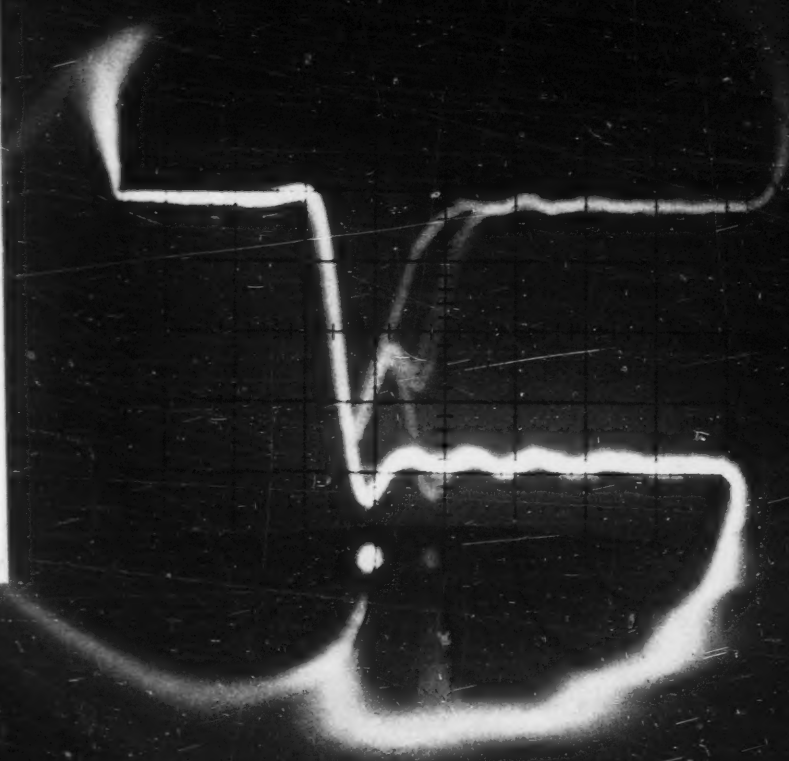

New materials and their uses

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CIRCLE **101** ON INQUIRY CARD

Future looks bright for high-performance ceramics

Recent R&D advances are making these materials practical as metal replacements, particularly in automobile engines.

Judith P. Sen
Strategic Analysis Inc.

ALTHOUGH THE USE of ceramics to fabricate products is several thousand years old, developments within the past 10 years have created enormous interest in the field and have led some observers to declare that we are on the verge of a second "stone age."

Interest is focused not on the traditional ceramic materials that are used in such familiar products as dishes, sinks, tiles, and bricks but, rather, on a class of ceramics known as engineering, technical, or, as they will be called here, high-performance ceramics.

Ceramics are defined as nonmetallic, inorganic materials that are processed with heat and/or pressure. High-performance ceramics are made from raw materials whose compositions are carefully controlled. These materials include boron nitride, boron carbide, sialon, silicon nitride, silicon carbide, and zirconia.

Depending upon the specific type of high-performance ceramic, these materials offer many desirable benefits including the ability to withstand high temperatures, resistance to corrosion, special electrical properties, special optical properties, wear resistance, hardness, strength, and biocompatibility.

For example, the hardness and wear resistance of some high-performance ceramics allow them to be used in cutting tools and bearings. Resistance to chemical attack has led to use in chemical processing plants as seals, valves, and pump components. Electrical properties make these materials useful in capacitors and piezoelectric devices, as substrates for integrated circuits, and as packaging for electronic devices.

Worldwide sales of high-performance ceramics are estimated to have been $5.2 billion in 1985. Packages and substrates for microelectronic devices accounted for $1.7 billion and capacitors for $1 billion.

The outlook for present applications is strong. The estimated overall growth rate is projected to be 16% from 1985 to 1990. Among the more dynamic segments are sensors with a projected growth rate of 28% per year, structural ceramics with 25%, and cutting tools with 20%.

This large existing market, with its attractive growth rates, is one of the reasons for the current intense interest in these materials. However, there are several other reasons.

A key consideration is the market for ceramic automobile engines. Although it is estimated that significant commercialization is at least another five years away, the market for high-performance ceramics in automotive applications is potentially worth several billion dollars. In contrast, 1985 worldwide sales of ceramics for automotive applications, excluding spark plugs, were roughly $180 million.

Reasons for using ceramics in automotive applications include both the functional and structural properties of the materials. Functional properties include electrical, magnetic, and chemical. Functional components currently being manufactured with high-performance ceramics include oxygen sensors, knock sensors, thermal sensors, fuel level switches, and spark plug insulators.

The important structural properties required for automotive applications include the ability to maintain structural integrity under high temperatures while hav-

ing densities that are less than those of the metals they replace. Structural components now being used include catalyst supports and ceramic fibers for fiber-reinforced metal pistons.

Examples of engine parts now in use are exhaust port liners for the Porsche 944 Turbo and turbine rotors for the Nissan "Fairlady." Isuzu Motors is using silicon nitride glow plugs and precombustion chambers. Isuzu has a policy of incorporating at least one new ceramic part into its cars each year.

New engine systems under development include adiabatic diesel engines and the automotive gas turbine. Adiabatic engines do not require a cooling system and thus are more efficient because combustion heat is not lost through cooling. In addition, the weight of the cooling system is eliminated, as is the need for cooling system maintenance. In an experimental adiabatic engine developed by Cummins Engine Co., ceramics are used as coatings for cylinder walls, cylinder heads, piston tops, and valve seats.

Gas turbines generate power by driving a rotating turbine with compressed high-temperature gas. Gas turbine rotors made of a high-performance ceramic, such as silicon nitride or silicon carbide, can be operated at 1400 C as opposed to metal superalloys which are limited to 1100 C. Ceramic turbines are expected to be 30% more fuel efficient than are conventional piston engines.

The U.S. Dept. of Energy has been supporting two major demonstration projects involving gas turbines that contain ceramic parts. In one project, researchers from Ford Motor Co. and Garrett Turbine Engine Co. are developing a 100-hp single-shaft engine. The engine has parts made with silicon nitride, silicon carbide, and lithium aluminosilicate. These parts include the turbine assembly, combustor liner, and flow-path housing.

In another automobile gas turbine project, scientists at General Motors Corp. are developing a 100-hp two-shaft engine. Using two shafts reduces the strain on each turbine rotor, allowing use of a wide range of ceramic materials.

Important materials for automotive applications are silicon nitride, silicon carbide, and partially stabilized zirconia. Silicon nitride offers high strength resistance to thermal shock and low thermal expansion, and it serves as an insulator. Silicon carbide is very hard and is a good heat conductor. Partially stabilized zirconia is a very strong material that is unusually resistant to catastrophic cracking within certain temperature limits.

The most general problems are reliability during use, reproducibility in production, and the cost of production. Reliability refers most specifically to the problem of ceramic brittleness.

The brittleness of ceramic materials, *i.e.*, their susceptibility to catastrophic cracking, has been a major drawback to commercialization. The brittleness problem is being approached by improving the properties of raw materials and also by improving processing techniques. Changes that have been made in raw materials include preparing materials at high levels of purity, introducing various additives, and making fine, highly uniform powders.

Among the processing techniques under investigation are hot isostatic pressing, injection molding, and slip casting. Hot isostatic pressing (HIP) reduces the porosity that is responsible for weakening the ceramic but requires long cycle times.

Injection molding allows rapid formation of complex shapes, but tooling costs are high and total volume is limited. Slip casting is suitable for producing complex shapes and tooling costs are low. Drawbacks to slip casting are long cycle times, limited volumes, and high labor intensity.

The problem of production reproducibility refers to the difficulty of achieving uniform physical properties not only from batch to batch, but within single batches. The lack of reproducibility is a major contributor to the high cost of manufacturing products from high-performance ceramics.

Another cost factor is the expense of finishing products. The hardness of high-performance ceramics can lead to complex, time-consuming machining or expensive grinding.

One final drawback is the lack of experience designers have with ceramics in the end-use industries. A major effort will be required to educate designers to

Estimated worldwide sales of high-performance ceramics, 1985

Product	U.S. dollars (billions)
Packages and substrates for microelectronic devices	1.7
Capacitors	1.0
Ferrites	0.9
Cutting tools	0.8
Piezoelectric devices	0.3
Structural ceramics	0.3
Thermistors, varistors	0.2
Total	5.2

Projected U.S. growth of selected high-performance ceramics

Product	Average annual growth 1985 to 1990
Gas and humidity sensors	28%
Structural ceramics	25
Cutting tools	20
Capacitors	14
Ferrites, resistors, and piezoelectric devices	14
Packages and substrates	10

Significant growth in automobile engine parts will begin after 1990.

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accept these materials and to design products to take advantage of ceramic properties.

Despite the problems, the market potential is recognized not only by companies that traditionally have been active in the ceramic area but also by many firms outside the ceramic industry that have become aware of the opportunities and are eager to participate.

Companies now involved in advanced ceramics research include established traditional ceramic firms, established advanced ceramic firms, small entrepreneurial firms, and large nonceramic companies that wish to diversify into advanced materials.

Participation in the industry can include supplying raw materials, processing ceramic shapes, making fully assembled parts, or combinations of these activities.

Corning Glass Works and Norton Co. are examples of established ceramic companies adapting traditional technology to new areas. Companies such as AVX Corp., Coors Porcelain, and National Beryllia are established firms completely devoted to advanced ceramics. Small entrepreneurial companies include Adiabatics and Lanxide. Among the large nonceramic companies entering the business are Honeywell Inc., Brunswick Corp., and Standard Oil of Ohio.

Awareness of the opportunities in high-performance ceramics has been spurred in part by the enormous effort taking place in Japan. Japan's Ministry of International Trade & Industry (MITI) has targeted the development of advanced ceramics as part of a national technology policy. Approximately 150 Japanese companies are involved in some kind of high-performance ceramics manufacturing activity, although in many cases these products represent a fraction of total sales.

Currently, Japan is recognized as a leader in the use of ceramics for electronic applications. For example, Kyocera is the world's largest producer of packages for integrated circuits. Other active Japanese companies include Toray, NGK Spark Plug, NGK Insulators, Hitachi, and the automobile manufacturers.

The high-performance ceramics industry is experiencing a period of rapid change. Although major increases in consumption may be a decade or more away, many companies are convinced of the enormous potential of the business and believe that obtaining future rewards will require taking risks now. No one is certain exactly what the industry will be like in 10 or 20 years, but many companies are determined to be active when the market for high-performance ceramics is fully developed. R&D

THE AUTHOR

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